LSSA PROJECT

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DEVELOPMENT AND VALIDATION OF A LIFE-PREDICTION METHODOLOGY FOR LSSA ENCAPSULATED MODULES

JUNE 8, 1977

JPL 5101-40

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under National Aeronautics and Space Administration Contract NAS7-100, for the U.S. Department of Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by DOE and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

5101-40

LOW-COST SILICON SOLAR ARRAY PROJECT

DEVELOPMENT AND VALIDATION OF A LIFE-PREDICTION METHODOLOGY FOR LSSA ENCAPSULATED MODULES

June 8, 1977

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ABSTRACT

This report outlines an approach to the development of a life prediction methodology for polymer encapsulated photovoltaic cell solar array hardware. The characteristics and output of an ideal life prediction model are described. Such a model depends on the development of quantitative intermediate relationships between the environmental exposure parameters and the basic chemical mechanisms of material aging. These are described conceptually along with suggested relationships which might be developed for two potential solar array failure modes, optical transmission loss and delaminations.

The use of accelerated/abbreviated testing in the development of a life prediction methodology is reviewed.

The distinction between testing to reveal failure modes and testing to define rates of degradation is presented. The point is also made that acceptance tests and performance tests which involve some degree of stress acceleration have very limited application to predicting module lifetimes.

This report presents a framework for integrating various technologies related to developing reliable long-life solar arrays. It is presented in this preliminary form as a basis for review, discussion and guidance in the formulation of program tasks to develop, evaluate and incorporate improved solar array encapsulation systems.

CONTENTS

I. INTRODUCTION

This report presents an outline of an approach to developing a life prediction methodology for LSSA encapsulated photovoltaic cell modules. The purpose of this report is to compile some guidelines and develop a framework for integrating the various past and ongoing encapsulant life testing and life prediction analysis efforts on the Encapsulation Task and for formulating work statements for future contracted programs on Life Prediction Methods and a JPL in-house study of encapsulant failure and aging mechanisms. The material presented, which is preliminary and incomplete, is written up for critical review and discussion. The relationships presented here are conceptual in this presentation, but are intended to be quantitative in practice. It is, in fact, the quantifying of these relationships which will provide the challenge in test design, measurement and analysis in the development of a useful life prediction procedure.

II. THE IDEAL LIFE PREDICTION MODEL

If a satisfactory Life Prediction Model (LPM) were available how would it be used and what results could be expected from it? It is expected that a quantitative description of the model design and its material properties would be inputs to the LPM along with a quantitive description of the predicted environmental stress-time history for a specific geographic location. The LPM output would be a predicted module life time distribution in terms of a specified performance decrement. This is represented in Figure 1 as the number of solar cells (or modules) per month (or year) exceeding a specified performance decrement (referred to as Failure Rate). Thus, for 10,000 new modules described quantitatively and installed in a well-documented environment, the life expectancy of that set of units would be described with considerable confidence by the curve of Figure 1 if a good LPM is assumed. This is the best that would be expected from an ideal LPM.

This point is stressed because the question can be raised, what is the life expectancy of one module? Or, one may ask, how can a minimum life of 10 years (or 20 years) be ensured? These questions would be answered by the LPM in terms of the most probable lifetime values and appropriate confidence limits. Every system subject to hazards or stresses has a finite probability of early failure. An approach to ensuring a minimum (10 yr.) life for most the modules would be to subject all 10,000 units to an appropriate acceptance test which would

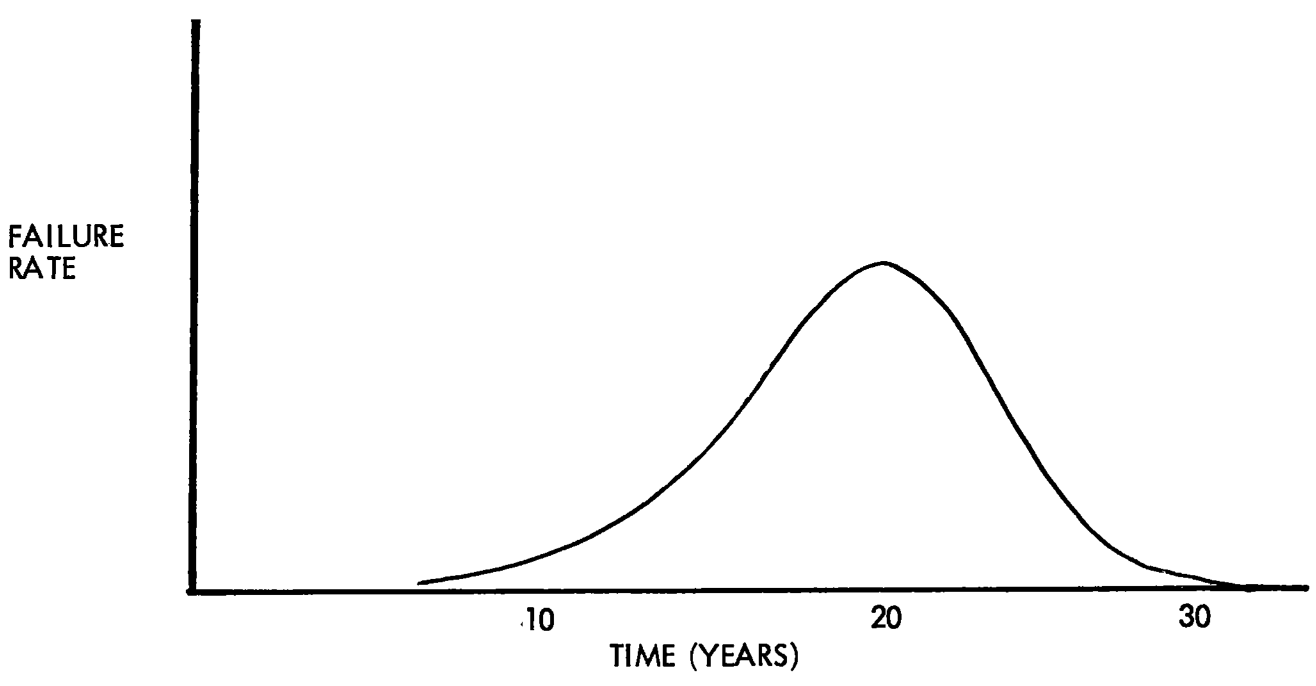

Figure 1. Failure rate distribution for solar array modules.

include some stress acceleration. The result (in practice) would be to weed out the weak units and give a skewed failure rate distribution for the remaining units. The ideal LPM could also be used to predict the skewed failure rate distribution by applying first the acceptance test stresses in the analytical model and then applying the subsequent predicted environmental stress-time input.

The foregoing describes the attributes of an ideal Life Prediction Model and its ideal application. With this ideal LPM available, it would be possible to track the field performance of the modules and react to some non-ideal situations. As statistical failure rate data would begin to accumulate and be compared to the results of the LPM prediction, one could investigate the causes of deviation from the predicted failure rate distribution. Was the weather more or less severe than predicted? Was some new stress imposing a performance limitation? Are there unaccounted-for variances in design or material properties? Is there some error in the modeling relationships not revealed in the validation testing? Corrective actions applied to the causes of the deviations at an early date could possibly improve the performance of the remaining units or of subsequently manufactured modules, or improvements in the Life Prediction Model itself could be formulated.

The development of an Ideal Life Prediction Model is an ambitious goal, but if the approach to its accomplishment is outlined in logical detail consistent with technical feasibility, then the various program efforts and experimental investigations now planned-for can be focused and coordinated in more effective manner.

It is anticipated in the future, when the solar array technology matures, that only one or two (at most) failure modes will determine the normal life expectancy of a solar array module. Which failure modes will predominate are presently unknown, but they could also vary with location (e.g., high desert vs. humid sea coast).

III. PROBLEMS IN DEVELOPING THE LIFE PREDICTION MODEL

This section describes some of the characteristics of solar cell array degradation and failure modes and some of the quantitative relationships which must be established before a Life Prediction Model can be formulated. In this preliminary report the following statements and concepts are compiled for more detailed consideration following their review and discussion.

(1) The development of a useful Life Prediction Model which will be used in predicting solar module lifetimes of 20 years and more must be developed and validated in a period much less than 20 years.

(2) The hope or expectation that solar array modules may last for 20 years or more is currently based on general experience with the basic materials. The general experience indicates that glass and some polymers could retain their useful physical, optical, and electrical properties for extended periods of years during outdoor exposure.

Specific experience with candidate solar array encapsulants reveals important degradation phenomena occur in periods of less than one year due to solar irradiation, temperature, moisture, and various atmospheric constituents.

(3) The development of a life prediction model basically requires that quantitative relationships be developed and validated among the individual and combined environmental stress elements and the individual module material and system degradation rates. Two obvious examples of degradation are the reduction in optical transmittance of a polymer as a function of ultraviolet exposure in specific wavelength bands, and the reduction in adhesive bond strength as a function of humidity. Both of these degradation modes would also be affected by material temperature levels. However, it is clear that making laboratory measurements or conducting outdoor exposure tests of these phenomena, while necessary, is only a small part of the life prediction modeling.

(4) An understanding of how the environmental stress factors (UV, humidity, temperature, etc.) interact with the encapsulation materials and the solar cell system and how these interactions result in failure must be developed. This would include some of the factors discussed in the following paragraphs.

The environment can result in two kinds of stress effects, reversible and irreversible. As the sun shines on the array, material temperatures rise and temperature gradients and strain gradients are produced. Interfacial stresses are produced between dissimilar materials as the materials expand. Cyclic temperature variations may produce reversible complex material dimensional changes and time dependent viscoelastic strain responses which may result in irreversible damage such as delamination. Moisture adsorption and desorption, which can also be reversible, may lead to complex strain effects plus local moisture concentrations at bonded interfaces and at corrosion-sensitive solar cell elements. The accumulation of surface dirt may be a reversible stress effect or it may be an irreversible effect in some situations.

The second kind of stress effect imposed by the environment are the irreversible phenomena generally referred to as aging. Here again two phenomena may be distinguished; accumulated physical damage or irreversible chemical changes in the materials exposed. The accumulated physical damage is usually caused by local material strains due to temperature, moisture and mechanical loads. Metal fatigue failures are the usual example of the result of damage accumulation.

Chemical changes with time may be induced by several factors including temperature, actinic radiation, moisture, chemicals in the air, chemicals in adjacent materials, impurities in the base material. The rate of change in the chemical structure (aging) will be some complex function of several of the foregoing effects. The effect of these material changes on cell performance may be manifested by a loss in solar transmittance and a consequent power loss or by a loss in interfacial bond strength or an increase in interface stresses due to physical characteristics with a consequent delamination. Irreversible changes in material properties such as modulus, elongation, hardness, and tensile strength may or may not contribute to actual encapsulation system failures. Other degradation modes such as corrosion or loss of electrical isolation may also be related to these irreversible stress effects.

IV. A SIMPLIFIED LIFE PREDICTION MODEL

In order to outline and integrate the many experimental and analytical steps necessary to the development of a life prediction methodology, it may be useful to consider two extremely simple models and follow their development. Starting with a very simple model and gradually increasing the complexity offers some insight into dealing subsequently with the complex realities of life prediction. Therefore, it should be kept in mind that the two initial life prediction models described in this section do not account for all the degradation interactions that can readily be described.

A. MODEL T: TRANSMITTANCE DEGRADATION

One can readily imagine a solar module cover material for which transmittance degrades with exposure time to solar UV in a specific wavelength band (e.g., 300-350 nm). If module power output were proportional to transmittance, then a predicted performance (η) curve in terms of the ratio of peak power at time (t) to initial peak power (t=0) would be plotted as in Figure 2.

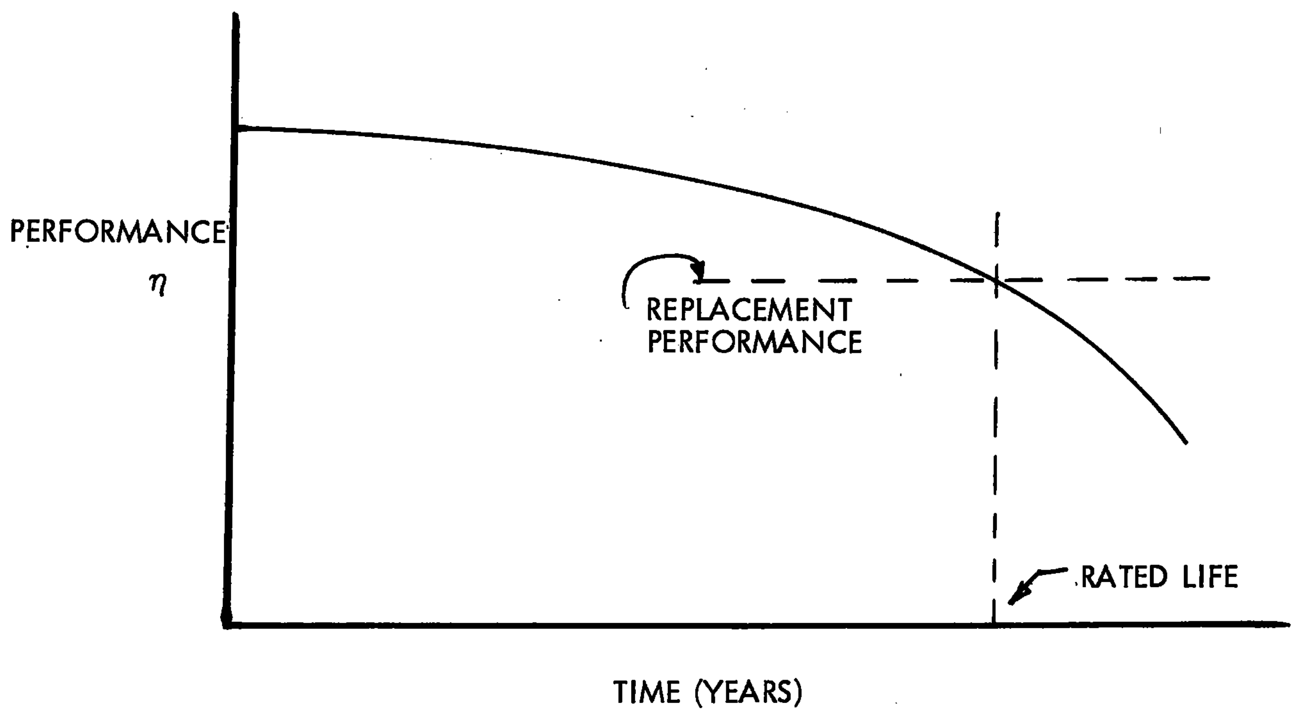

Figure 2. Solar module life time performances due to UV degradation of cover material.

For this degradation mode, failure would be defined as a specified performance decrement determined from the economics of module replacement costs. In this simple example, it is assumed that all cells in the module degrade uniformly because they all receive the same radiation dosage. The predicted curve of Figure 2 can be visualized as being derived from several other curves. One set would be the UV environment curves shown in Figures 3a and 3b. The other useful relationships, if they could be established, would be the time rate of change of cover material transmittance ($\dot{\tau}$) as a function of UV intensity and wavelength, cover thickness, and temperature. Such a plot could be as shown conceptually in Figure 4a or 4b.

Having all the necessary data available on the spectral energy distribution of the anticipated solar exposure, and having the cover material degradation rate relationship, one would also have to predict the cover material temperatures as a function of time. An additional complication would arise if the degradation rate curves were not linear up to the normal solar intensity. If the degradation rate curves were linear to the normal solar intensity, but became non-linear at increased UV intensities that would be associated with accelerated testing, these relationships would have to be carefully evaluated and understood. It is expected that the degradation rate will also be related to total exposure time or damage accumulation, as noted in Figure 4.

For this simplified model, linearity is assumed. Combining these curves and exaggerating the results would give the life prediction curves in Figure 5. The problem immediately apparent is that the rates of degradation on a daily basis, or the total amount of degradation over a relatively short time (measured in days or weeks) would be very small if the total degradation decrement over 20 years is to be reasonable (say 15%). The decrement for one day would be 0.002%, and for one year, the loss in transmittance would be 0.75%. It would be helpful if the transmittance loss were proportional to the cumulative UV radiation measured within discrete wavelength bands. This could be readily measured in the field.

The formulation of a dimensionless correlating parameter to combine the effects of UV intensity and temperature could also be useful, but its validity would have to be established by experiments in which the separate effects of each variable were quantitatively measured. The foregoing relationships could provide the basis for a computer model which could use module design material properties and dimensions along with a projected stress (UV and temperature) environment to predict the lifetime to a specified performance decrement. Such a model would be deterministic, in that each module description would result in only one value of lifetime. A probablistic model would result if the potential uncontrolled variation in material initial properties and variable degradation rates due to impurities and processing variables were included in the design input properties, and if the potential variability of environmental characteristics were used to define the environmental stress factors. The resulting graphical presentation is shown in Figure 6.

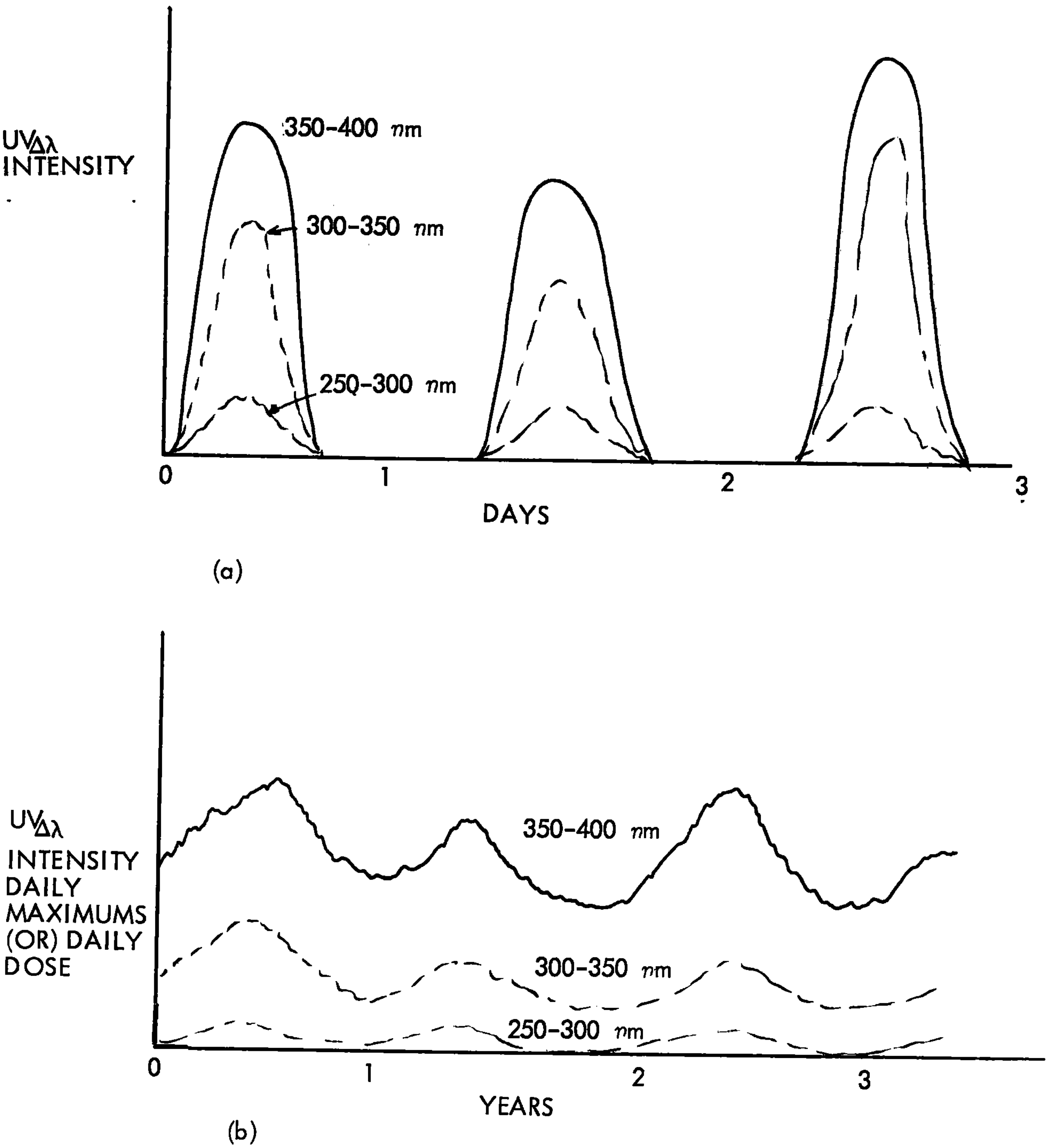

Figure 3.a-b. Daily variation in UV intensity and yearly variation in maximum UV intensity.

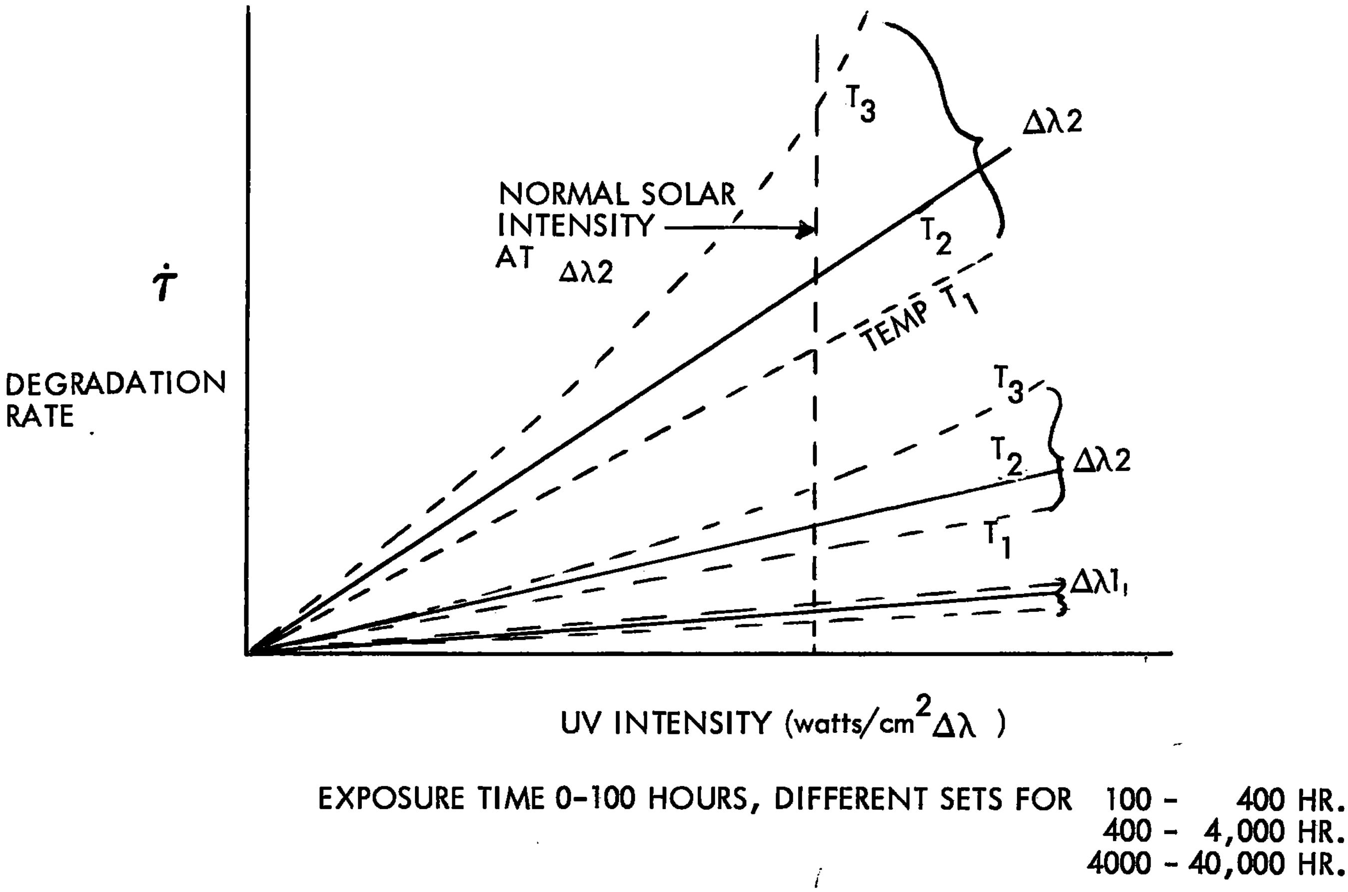

Figure 4a. Rate of degradation of cover material exposed to UV.

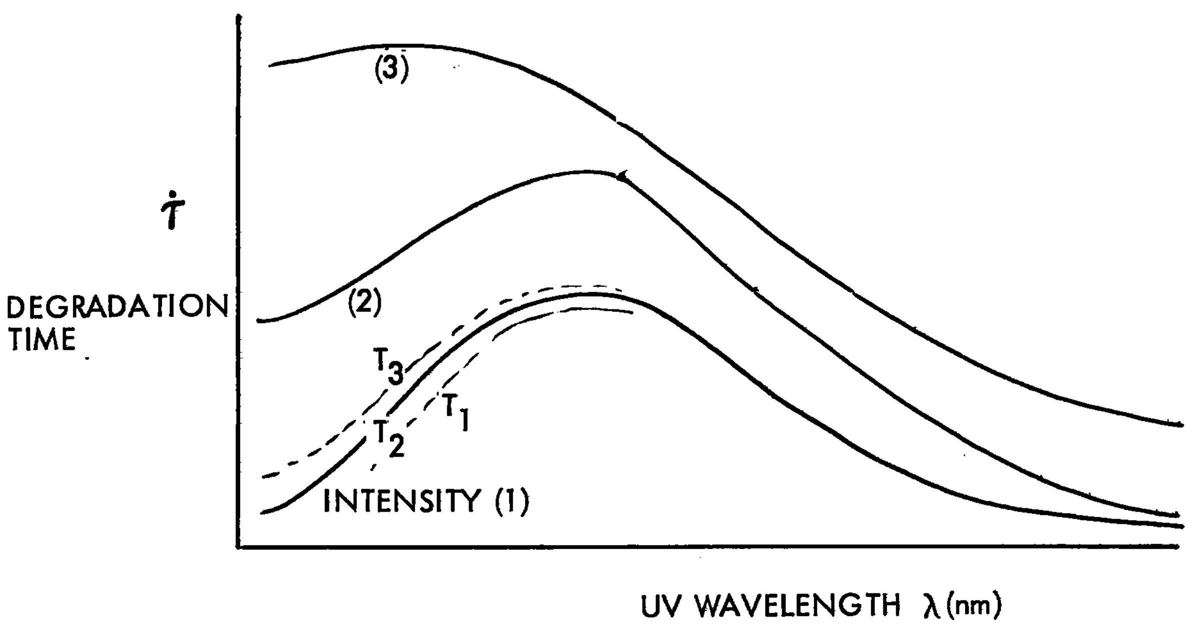

Figure 4b. Rate of degradation of cover material exposed to UV.

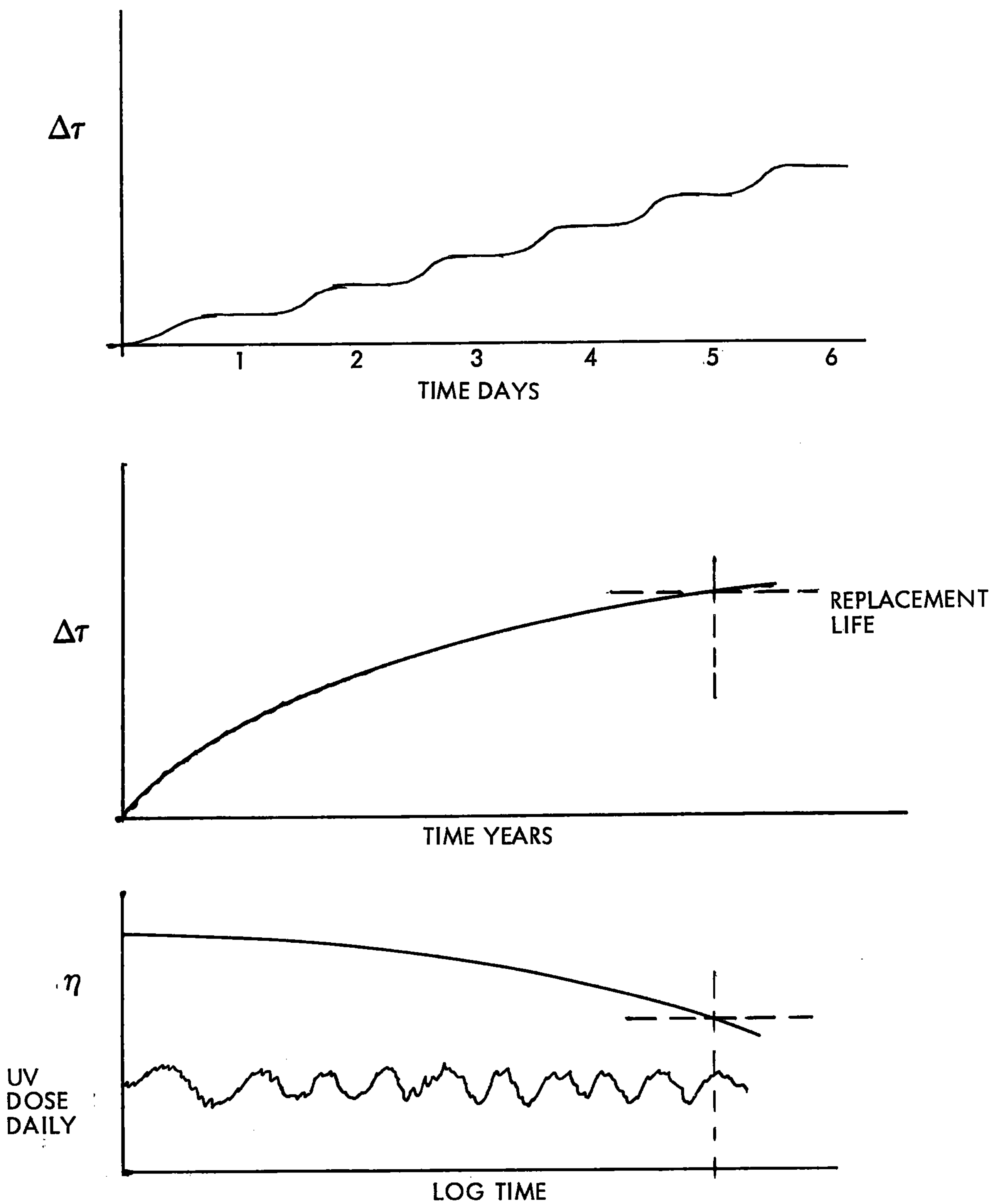

Figure 5. Module degradation and module performance.

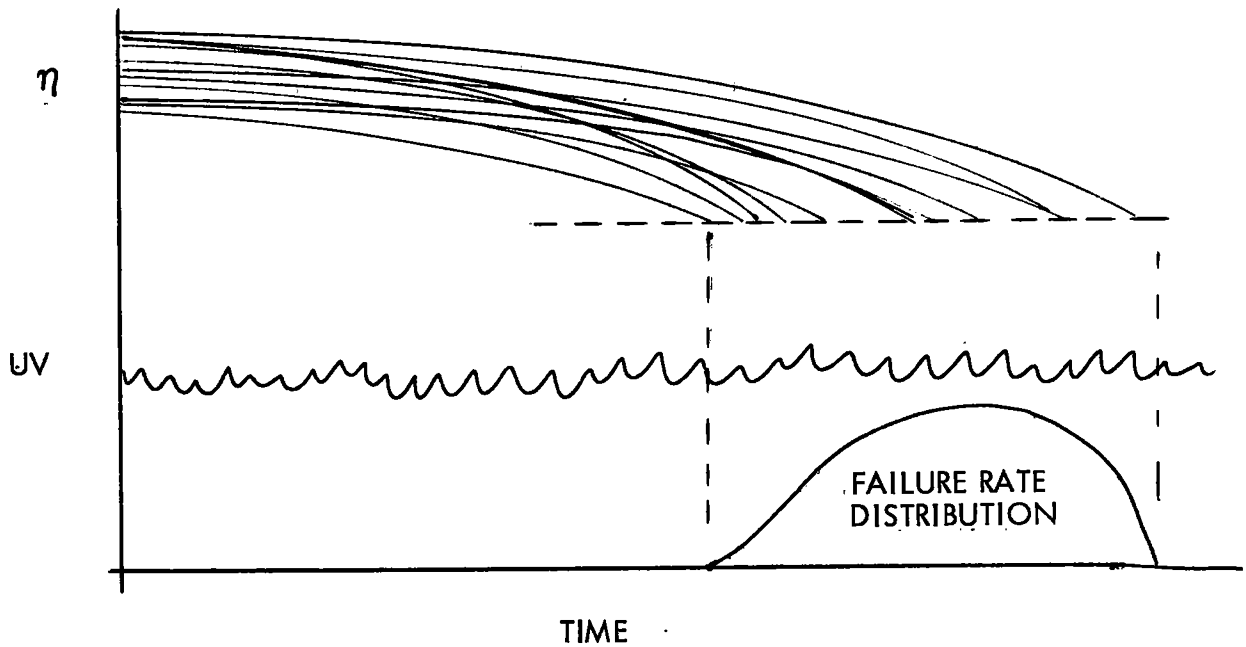

Figure 6. Failure rate distribution due to variable stress and variable design parameters.

The foregoing transmittance degradation model is greatly simplified. Added complexities may be introduced as their importance is assessed from separate analytical or experimental studies. One such added complexity is the spectral variation in absorbed UV as a function of solar radiation angle of incidence at the module surface. This would vary daily as well as annually. This effect may be further compounded by the sensitivity of the degradation rate to radiation wavelength distribution and the steep curve of UV intensity versus wavelength at the earth's surface, and its variation with sun angle, season, and geographic location.

In a module cover design composed of two materials, one may be glass or both may be polymers. The glass cover may have an added antireflection coating. The combined effect of such composite cover systems on the spectral transmission and absorption of UV and the resulting degradation rates introduces further complexity. How these combined effects can be lumped together experimentally or in empirical correlations remains to be determined. Their relative importance may be investigated both analytically and experimentally. Probably, a combination of both approaches would prove most effective.

All of the foregoing development of a simple Life Prediction Model assumes the availability of sufficient accurate experimental data to uniquely define the encapsulant degradation rates over a 20- to 30-year module exposure time. At the present time neither the environmental data nor the material aging characteristics of sufficient accuracy have been collected or measured. Plans for accurate documentation of the environmental UV characteristics of incident solar radiation at various geographic locations are being implemented.

One approach to determining accurately the aging characteristics of polymers exposed to solar UV would be to find and measure some key chemical structural change which would be proportional to total absorbed UV in a selected UV band and also related in a simple way to total transmittance changes. Figure 7 shows an example of how measuring a chemical change could provide accurate determination of small transmittance changes.

Development of this intermediate relationship for each material would also require determination of the simultaneous effects of temperature, humidity, material thickness, material purity and processing history as well as the effect of UV spectral intensity and distribution.

Statistical test design and the use of accelerated test conditions are considered later in this report.

B. MODEL D: DELAMINATION

Visible delamination in a solar cell module between the cell cover material and the silicon solar cell or between a glass cover and the polymer encapsulant has been defined as an encapsulant failure mode. When these delaminations occur after a short time of performance testing or accelerated acceptance testing, they are often random in character and attributed to problems in processing or process control. Such early failures in similar manufactured systems are referred to as "infant mortality." Experience during the early life of many industrial products shows a subsequent reduction in failure rate until a later time in service when aging or wear-out effects begin to predominate. The obvious

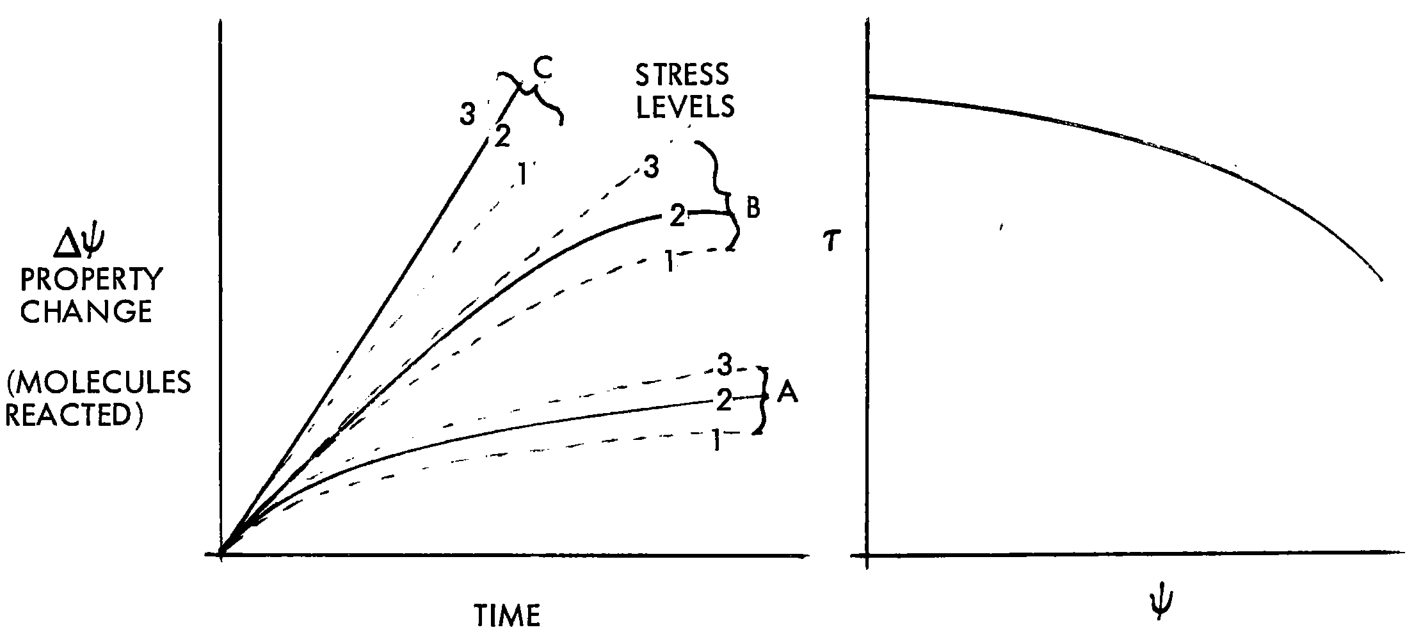

Figure 7. Polymer property changes related to UV and transmittance.

implication of this phenomena is that short-time failure rate data obtained during performance tests and short time accelerated exposure tests cannot be extrapolated to predict future failure rates.

In the following development of a Life Prediction Model related to the delamination failure mode, the approach is developed conceptually and graphically starting with a simple example and identifying some of the complexities which must eventually be included. Some specific contrasts between the delamination model and the transmittance model are described.

For the delamination model, the assumption is made that delamination occurs because the stress (shear or normal tensile) in the interfacial bonds or adhesives exceeds the bond strength at the interfaces. Two typical failure geometries are shown in Figure 8. The maximum stresses due to differential expansion strains may be shear at the edges or buckling at the center.

The quantitative effect of delaminations on cell performance has not been carefully evaluated. Furthermore, the effect of one or more delaminations on module (50 or more cells) performance is even more uncertain. For the purposes of this example, it will be postulated that each module consists of one cell and a delamination produces complete module failure. It is postulated that each interface bond has a specific allowable shear and tensile strength (referred to as F_s and F_t or simply F). It is also postulated that the interface stresses can be calculated as a function of the material properties and the applied mechanical and thermal loads. These loads would be a function of heat transfer to, within, and from the module by conduction, convection and radiation. Wind loads, warpage, and moisture absorption would introduce additional strains. Also, since the polymers are viscoelastic in nature, the sudden application of a constant load will produce time varying strain and stress responses. Also, there may be reversible changes in adhesive bond strengths with moisture absorption and desorption. Thus, we have the makings of a very complex set of interactions even for the simplest failure mode example.

Before considering the effects of aging one may graphically present the interactions discussed above as represented in Figure 9. The curves of Figure 9 as drawn imply no bond failures because the interface stresses don't exceed the bond strength. In reality there would be a distribution of minimum bond strengths for each of many modules and a wide range of

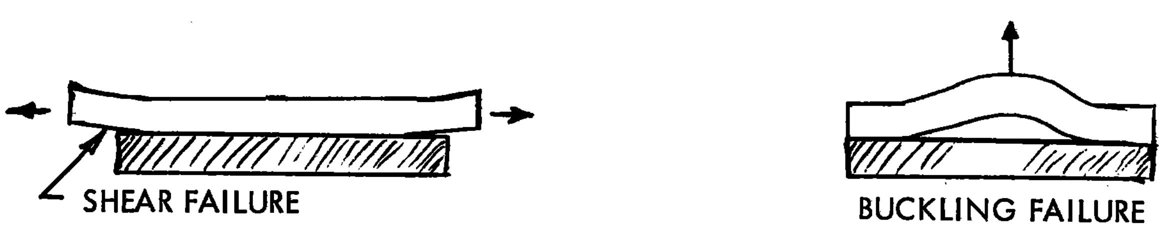

Figure 8. Two types of delamination failure due to differential expansion strains.

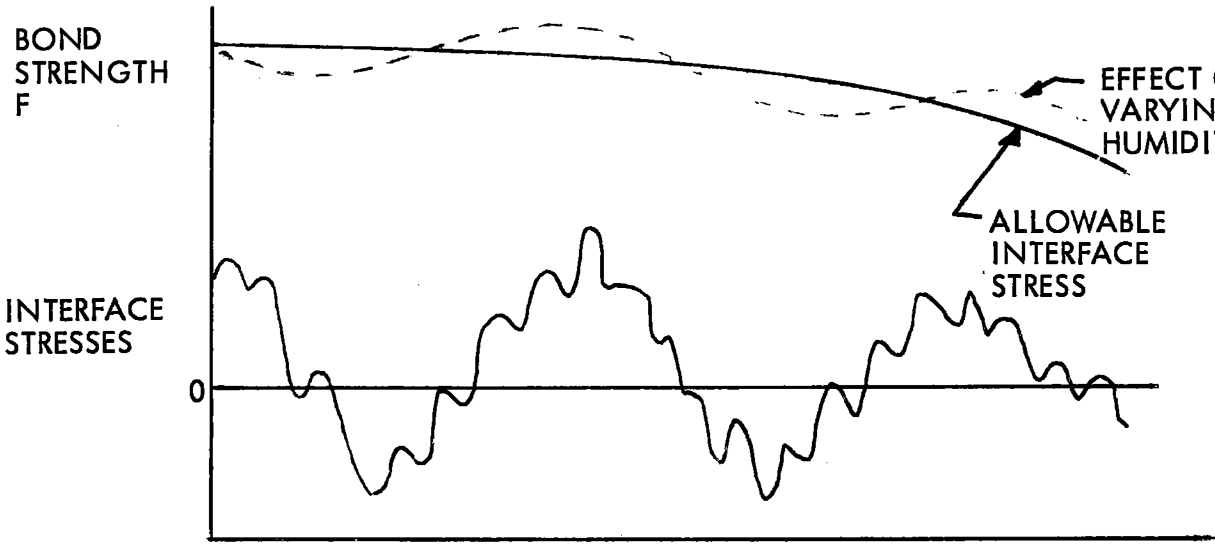

Figure 9. Allowable interface stresses and applied stresses due to outdoor exposure of encapsulated module.

stress levels over the surface of each module during the daily and seasonal exposure to environmental stresses. Failure by delamination is postulated to occur when the applied stress at a specific spot on the module exceeds the bond strength there.

The effect of aging may be manifested in two basic ways. Aging may decrease the bond strength, and also, aging may alter the material physical properties which could change the resultant stress response to the environmental inputs. The resulting failure picture is shown conceptually in Figure 10, which indicates both decreasing allowable stresses and increasing applied stresses.

Examination of Figure 10 reveals several characteristics of the delamination failure rate distribution to be considered when interpreting field test data or in planning performance or reliability tests. First, the delamination failure rate distribution would be polymodal and likely related to weather changes. During periods of extreme weather changes or specific weather element combinations an increase in delamination failures would be expected, with a subsequent reduction in failure rates during mild weather. Second, examination of the initial rates of failure would provide only limited insight into subsequent failure rates because the remaining modules would be characterized by both different initial properties and differing degradation rates. However, it could be expected that properly designed accelerated stress acceptance testing could be used to screen out modules potentially subject to early failure. Accelerated testing data would provide little insight into the predicted life of the remaining acceptable modules.

An important aspect of the real problem associated with delaminations is assessment of the actual performance decrement experienced due to delamination. Two factors entering in to this evaluation would be

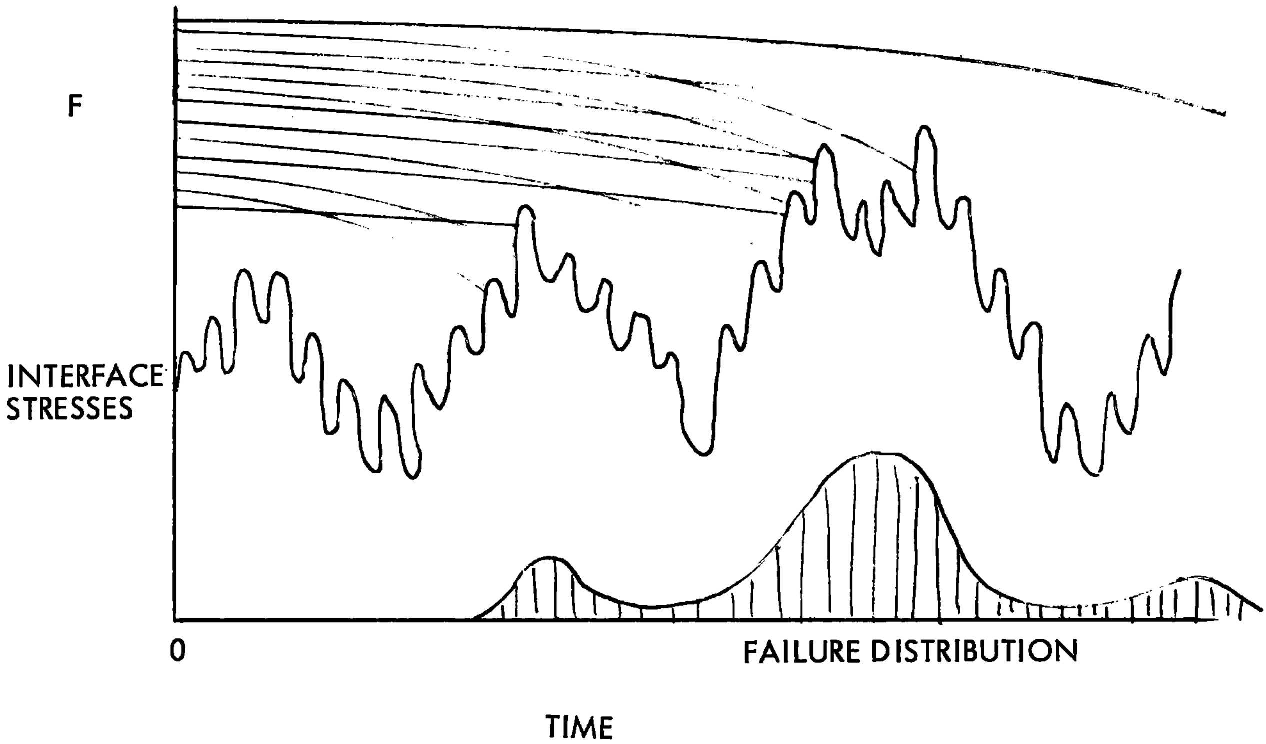

Figure 10. Failure rate distribution due to the interaction of several aging modules with time varying applied stresses.

the loss in performance as a function of the size and location of the delamination, and the effect of continued cyclic environmental conditions on delamination growth (damage accumulation) once it has been initiated.

These two foregoing examples of failure mode characterization (transmittance loss and delamination) illustrate the kinds of data and quantitative relationships necessary to the development of a life prediction model. For other modes of failure such as corrosion, electrical breakdown, and fatigue of interconnects, similar relationships must be experimentally defined among losses in performance, the failure mechanisms, the rate of changes in properties and the levels of stress or the integrated stress-time loads on the module.

The use of accelerated environmental testing to gain insight into these failure mechanisms and to assess the sensitivity of the failure processes to various levels and combinations of stress is discussed in the following section.

V. ACCELERATED ENVIRONMENTAL TESTING AS APPLIED TO LIFE PREDICTION

Accelerated environmental testing is a general term used to include both abbreviated testing and testing in which acceleration is achieved by increasing the frequency of the stress cycles and/or the intensity of the stresses (e.g. UV, temperature, moisture, etc.). Details of past and current accelerated test programs, methods, measurements, and materials are given in numerous LSSA reports including the encapsulation system test reports of Battelle, Rockwell International, and Springborn Labs. Performance and acceptance testing being conducted under the LSSA Operations Area at JPL and elsewhere have some accelerated stress conditions included in them to evaluate module durability and failure modes.

Four differing objectives may be defined for programs employing accelerated testing conditions. All four objectives will be involved in the development of reliable solar arrays with a 20-year life expectancy. These four test objectives may be expressed in terms of the testing necessary to provide answers to the following four unknowns:

a. Unknown performance

b. Unknown reliability (failure modes)

c. Unknown lifetime (replacement interval)

d. Unknown rate of performance degradation.

In experimentally evaluating these unknowns, the same test item or test specimen designs may be used, and the same types of environmental stresses may be imposed. However, there may be great differences in the severity of test conditions, the intervals of severity, in the numbers of replicate tests, and in the analysis and interpretation of the test data.

The chart of Figure 11 outlines four differing approaches to accelerated environmental testing to achieve four different test objectives. The characteristics of these four types of testing programs are described briefly in this section to indicate their relationship to the development of a life prediction methodology.

Introductory to consideration of each test type, the following definitions of the chart nomenclature are presented.

a. Design - Defined as the test specimen description including the material and material properties, the configuration geometry and dimensions, and the handling and processing history which could affect the initial state of the test item.

b. Stress - Defined as all elements of the testing environment which can be characterized and which would have some bearing on the responses of the test item. These would be referred

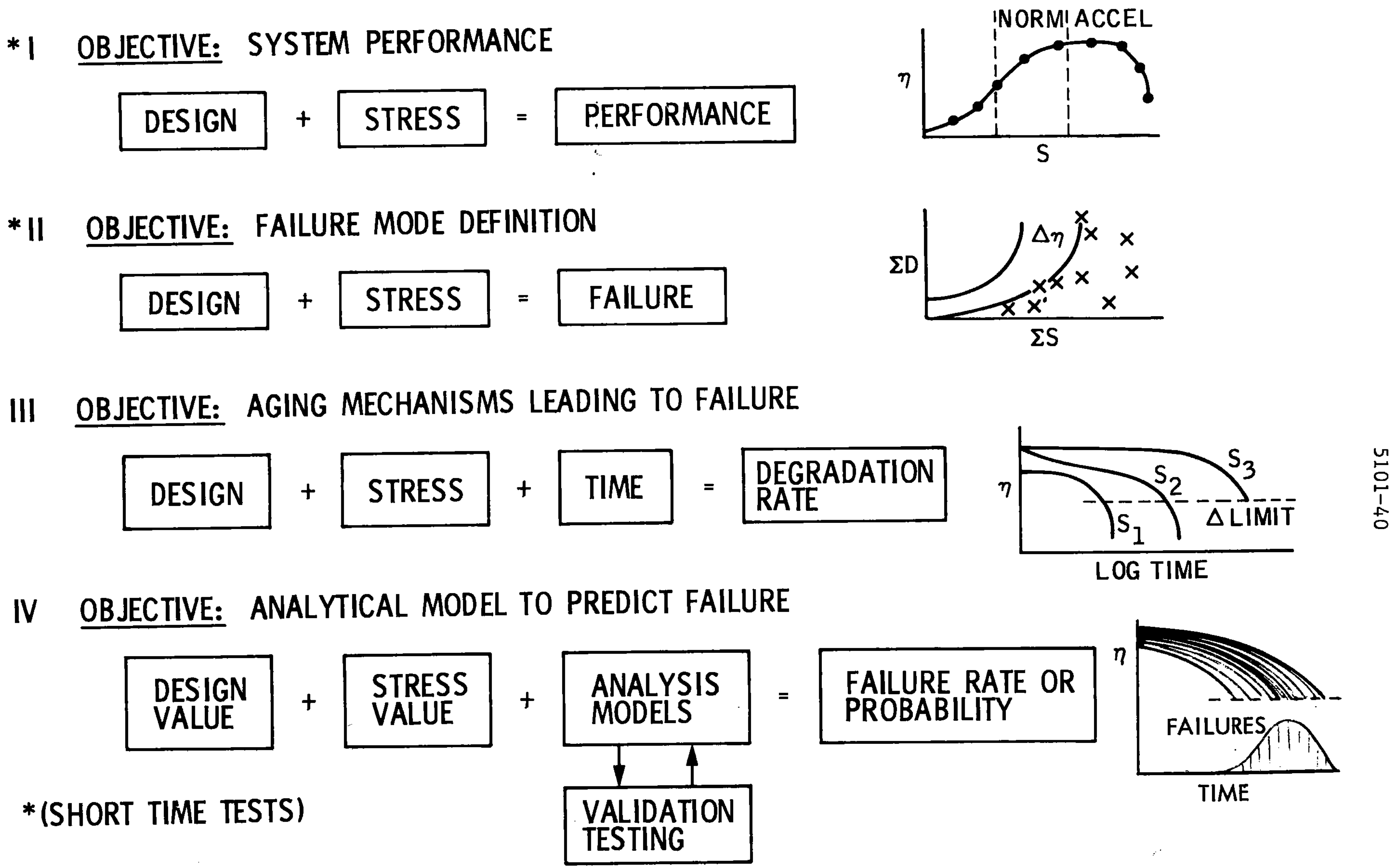

Figure 11. Accelerated environmental testing differing test objectives.

to as the test conditions or parameters. These would include the physical surroundings, the irradiation intensities versus wavelength, angle of incidence and time, plus humidity, wind, air temperature, air pollutants, precipitation, and imposed mechanical loads.

c. Performance - Defined as the measure of merit in fulfillment of the intended design function. Performance may be expressed as useful outputs as a function of the values of each stress parameter or as a percentage of an ideal value, an initial value or a design-rated value.

d. Failure - Defined as a permanent (irreversible) degradation in the test specimen properties resulting in a performance decrement. Failure is usually construed as a performance decrement great enough to require repair or replacement of the item in service. Modes of failure include cracks, corrosion, electrical open circuit, leakage or shorting, loss of optical clarity, delaminations, etc.

e. Degradation Rate - Defined as progressive rate of property or performance degradation during the testing period prior to reaching the performance degradation limit requiring item replacement or repair.

f. Failure Rate - Defined as the time distribution of the number of test items exceeding a specified performance decrement.

g. Validation Testing - Defined as testing conducted at values of design and stress parameters which have been previously used as inputs to a performance prediction model to forecast the test results. The prediction model used may be a simple extrapolation based on a previous series of tests at similar conditions or the prediction model may be a complex analytical computer model capable of forecasting test item performance over a wide range of untested design and stress combinations.

The chart of test objectives in Figure 11 presents a normal sequence of development testing tasks. First, the development prototype of a device would be experimentally evaluated to see if and how well it performed its intended function at normal operating conditions. If initial performances were totally unsatisfactory, it would matter little how reliable the item was or what the failure modes were. Of course, there is some overlap in objectives in all these testing tasks, but they are separated here for the purposes of discussion.

A. OBJECTIVE I: SYSTEM PERFORMANCE

Performance test parameters are normally varied over the expected range of operating conditions. Some stress acceleration may be introduced by the time compression of the varying operating environment.

Where performance curves are generated as a function of stress level, stresses above normal are applied in order to generate a complete map of performance versus stress characteristics such as in Figure 12. The two primary characteristics of performance testing to meet Objective I are that the tests are non-destructive and repeatable and that time is not a basic parameter in the performance evaluation. (Time may enter the evaluation where rates of change of parameters influence performance.) Some tests run to meet Objective I are called qualification or acceptance tests and production items so tested would be expected to be undamaged and put into service and operated over a normal lifetime. Tested production items which did not pass an acceptance test, due either to low performance or a component failure, could be rejected in the process of weeding out weak units from a statistically variable product. These tests results would not necessarily contribute to meeting the objectives of the second type of accelerated testing described below.

B. OBJECTIVE II: FAILURE MODE DEFINITION

In conducting a test program to meet Objective II, a wide range of combinations of both design and stress parameters would be encompassed. Since neither the modes of failure nor the combinations of stresses producing failure may be known initially, the systematic variation of all parameters may be impractical from time and cost considerations. Judgment, intuition, and related experience may guide in the judicious selection of the initial test parameter combinations. Test severity may be set at values that are high, normal, and low. The initial output of such a testing program could be the formulation of a failure envelope as shown conceptually in Figure 13 with axis coordinates of

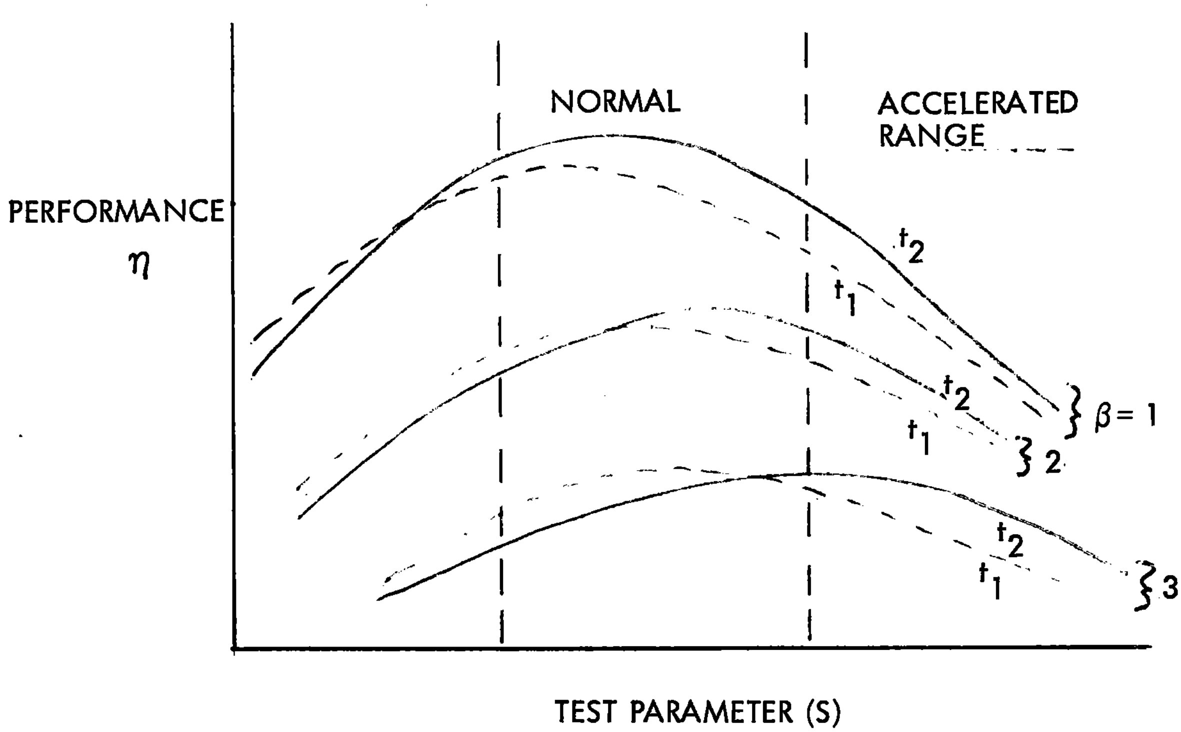

Figure 12. Typical performance test results.

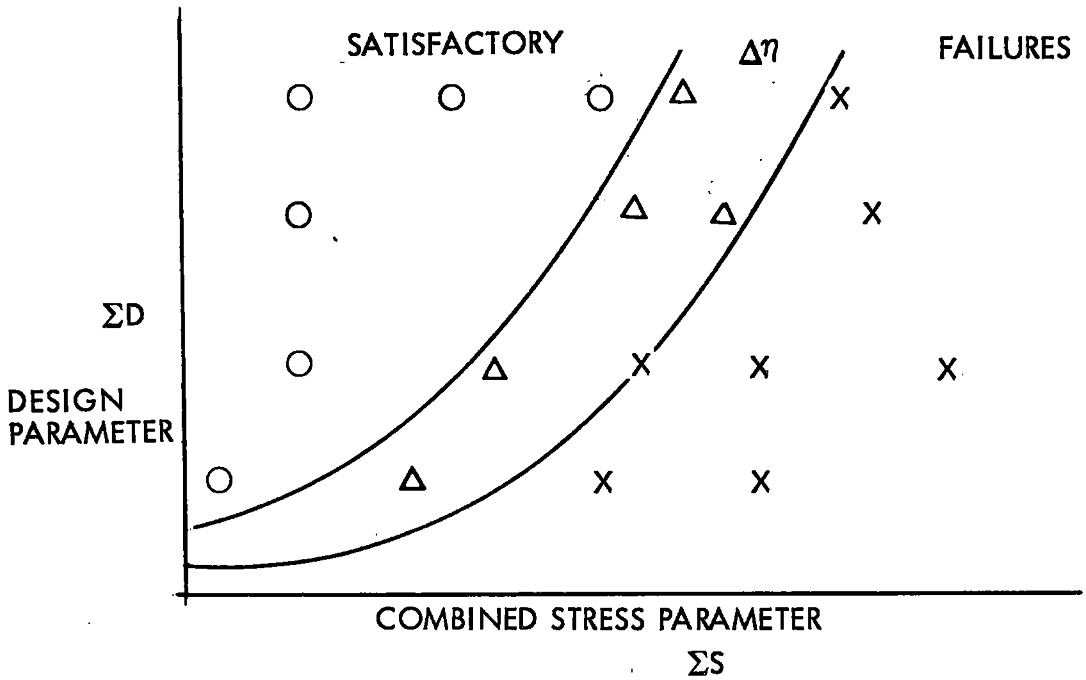

Figure 13. Failure envelope defined by testing various combinations of design and stress parameters.

a combined design parameter function and a combined environmental stress function. The failure cases could represent one, or more than one, failure mode. The graphical presentation of test results in Figure 13 might result from a series of test items containing design parameter variations such as material thickness, modulus, expansion coefficient, adhesive type, glass transition temperature, and initial transmittance. The combination environmental stress function, which could include temperatures, humidity, and solar intensity, could also include a time function in terms of a total irradiation dose or number of stress cycles or rates of change of stress. Time, in terms of a 20-year lifetime, would not be included as a basic parameter in this phase of failure mode identification. In the process of failure mode identification from short-term testing, it would be beneficial to classify failure modes in terms of those associated with the initial design parameters and fabrication processes as distinguished from those failure modes related to time itself such as wear, fatigue, crack growth, corrosion, or loss in transmittance. Degradation modes which have threshold stress limits may be controlled by module designs in which the threshold stresses are not initially exceeded at normal operating conditions. With material aging over a period of years, changes in physical properties may occur, and the stressing situation may change, exceeding the threshold for degradation, thus resulting in gradual or rapid performance losses.

The concept of a maximum damage limit should be investigated during this testing phase. There are several types of failure or material degradations that would be limited in extent regardless of the severity and time of testing. Solar transmittance is one example. The total transmittance through a polymer cover sheet would probably remain at some value above zero no matter how long the material was exposed. Also, delamination between the solar cell and its cover material would result in some limited transmittance decrement even with total delamination. The determination of these damage limits should be a goal of Objective II testing.

A distinguishing characteristic of Objective II testing is that the test produces some measure of permanent damage in the test item. Also the tests are usually run over a relatively short time compared to the total design lifetime. Normal aging and wear would not be primary causes of the failure or damage identified.

In the special cases for which failure or wear can be quantitatively related to the number of stress cycles, and the number of stress cycles over a normal lifetime can be closely estimated, then the life of the test item could be predicted. Many mechanical devices with moving parts fall into this category. A potential solar array failure mode falling into this category may be the rate of growth of a delamination spreading from some initial flaw or edge condition. The goal of Objective II testing would be to determine the existence of such failure modes and their sensitivity to the various imposed environmental stresses. Thus testing with a large range of stress intensities may give insight into selecting future stress parameters and stress level intervals for evaluation of degradation rates and aging mechanisms.

C. OBJECTIVE III - EVALUATING AGING MECHANISMS LEADING TO FAILURE

In evaluating system and material aging mechanisms leading to failure, the primary objective would be to quantitatively determine rates of degradation or rates of change of measurable system characteristics as a function of each separate or combined environmental stress over long operating times. For systems with 20-year lifetimes, the rates of degradation over short test periods may be very small and require great precision in measurement. It would be important to define the physical nature or mechanisms of short and long term degradation. This may come from direct observation, past experience, or an experimental study of similar physical or chemical systems. Three characteristic performance degradation curves which may be identified are of the form shown in Figure 14. Analytical expressions and physical phenomena producing these characteristic degradation curves can readily be formulated. Their experimental verification may be much more difficult. However the importance of determining the form of these curves is obvious in being able to extrapolate from 2 years to 20 years.

Very complex curves may result from the combination of multiple or competing failure modes. Objective III testing requires a systematic, parameter-by-parameter evaluation of each degradation mode. These tests must be performed under completely controlled and characterized experimental conditions. Fluctuating conditions encountered in normal or accelerated outdoor exposures may aid in identifying failure modes and in indicating relative sensitivities, but controlled exposure conditions are required to establish the precise degradation rate relationships required for predicting lifetime performance up to 20 years or more.

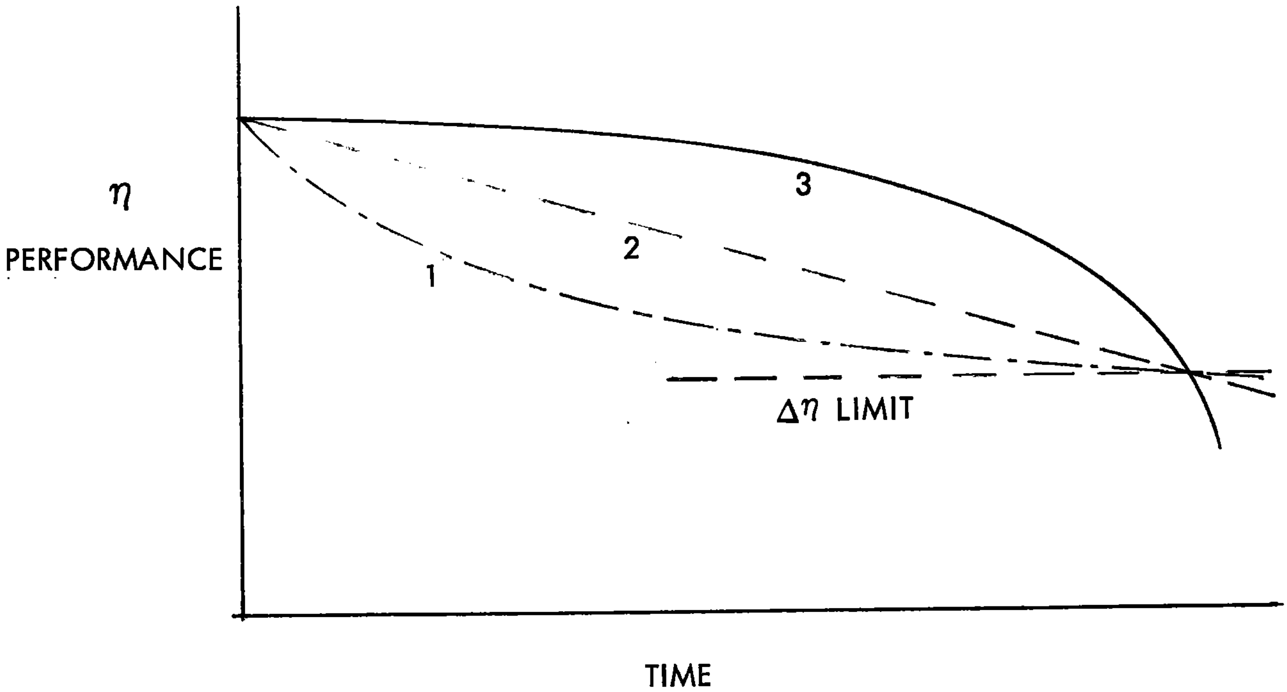

Figure 14. Typical performance degradation curves determined by differing aging and degradation mechanisms.

After having identified various failure modes during Objective II testing of complete modules under normal or accelerated exposure conditions, it may be necessary to test sub-components or materials alone to quantify rates of degradation as a function of each stress element alone and in combination. At the point of departure from complete module testing at normal environmental exposure conditions, it would be important to understand and define the connecting quantitative relationships between the laboratory aging studies and the outdoor exposure tests. The laboratory testing must be conducted at stress conditions which will encompass outdoor stresses and which can be measured during outdoor testing. Thus, determining the rate of aging of polymers due to solar UV requires laboratory application and control of the spectral distribution and intensity of radiation covering the potential outdoor conditions. Then in predicting or validating the rate of outdoor aging, it would similarly be necessary to specify or measure the spectral distribution and intensity of normal solar irradiation falling on a test module.

The identification and precise measurement of a secondary chemical or physical material characteristic would aid in life prediction if the change in the measured characteristic (ψ) could be related both to the rate of performance degradation and to the stress intensity/time function. These relationships are shown conceptually in Figure 15.

The statistical design of tests to produce the key quantitative relationships shown in Figure 15 has been discussed by both Rockwell International and Battelle in their investigations of accelerated testing methods. It is the accurate formulation of these key intermediate

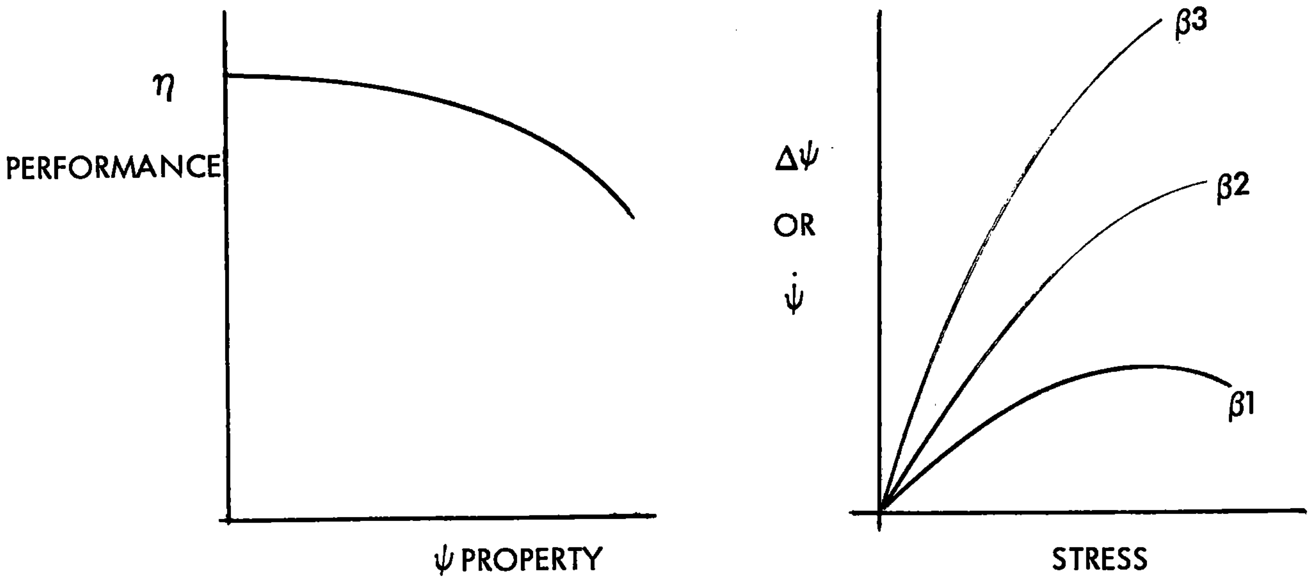

Figure 15. Relating performance loss (η) to secondary (ψ) property changes resulting from environmental stresses.

aging rate relationships which will be the basis for a satisfactory life prediction methodology. The development of reduced variables in which several stress parameters could be combined in a single variable would reduce the complexity of the life prediction model. This is facilitated by initial separation and control of the test stresses. This effort also may require a very extensive test matrix and precise control of test parameters. Preliminary experimental studies may be conducted to determine the required range of test variables, the test precision required, and the basic form of the resulting rate curves. Thus, Objective III testing may occur in two or more phases in developing the necessary quantitative aging relationships.

D. VALIDATION OF THE LIFE PREDICTION MODEL

The foregoing discussion of the development of degradation rate quantitative relationships indicates that they are best developed under laboratory conditions and closely controlled exposure conditions. The validity of such relationships must then be established under full-scale field exposure conditions for which the environmental stresses may be imposed in a highly variable and random manner. Exercising the analytical models over selected ranges and combinations of environmental stresses will provide an evaluation of the accuracy required in specifying and measuring the variations in environmental parameters such as insolation, temperature, humidity, wind velocity, etc. In some cases integrated values or daily averages may suffice to predict total degradation during a given period.

In validation testing, results should be predicted prior to testing based on predicted stresses and again, after testing, based on measured environmental parameters. The prediction model should be probablistic to yield a range of probable test results based on the experimental variability of design properties and material aging rates. The number of validation tests and the selection of test parameters should be based on the requirements for statistical validity at confidence levels consistent with other elements of the overall solar power program.

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